Appendix A

Flat Panel Display Technologies[30]

Technology	Description	Applicability to DfE Project
Liquid Crystal Displays (LCD)	A liquid crystal material, acting like a shutter, blocks, dims, or passes light unobstructed, depending on the magnitude of the electric field across the material.[31] A backlight provides the light source.	Included in the DfE Computer Display Project life-cycle study. Descriptions of the subtechnologies and whether or not they are included in the study are presented below.
(1) Passive matrix (PMLCD)	Liquid crystal (LC) material is sandwiched between two glass plates, which contain parallel sets of transparent electrical lines (electrodes) in a row and column configuration to form a matrix. Every intersection forms a pixel, and the voltage across the pixel causes the LC molecules to align and determines the shade of that pixel.[32]	Traditionally for low-end applications (e.g., calculators, wrist watches). Higher end applications use a super-twisted nematic (STN)[33] construction. The liquid crystal material is twisted between 180 and 270 degrees, which improves the contrast between the "on" and "off" states, resulting in a clearer display than with the twisted nematic (twisted only 90 degrees.[34] However, cost and performance issues limit this technology from wide application in the desktop market, therefore, it will not be evaluated in the study.
(2) Active matrix (AMLCD)	Similar to the PMLCD, except an electronic switch at every pixel provides faster switching and more shades. The addressing mechanism eliminates the viewing angle and brightness problems suffered by PMLCD. Requires more backlight than PMLCD due to the additional switching devices on the glass (at each pixel). Various switching types are listed below:	Provides vivid color graphics in portable computer and television screens.[35] This technology meets the functional unit specifications in this study. Specific subcategories are described below.

30 Socolof, M.L., et al., Environmental Life-Cycle Assessment of Desktop Computer Displays: Goal Definition and Scoping, (Draft Final), University of Tennessee Center for Clean Products and Clean Technologies, July 24, 1998.

31 Office of Technology Assessment, *Flat Panel Displays in Perceptive*, OTA-ITC-631, Washington, DC: U.S. Government Printing Office, September, 1995.

32 Ibid.

33 Traditional light modulating methods for LCD technologies include twisted nematic (TN), super-twisted nematic (STN), double STN, triple STN, and film-compensated STN. The STN is the current standard for high-end PMLCD applications.

34 Office of Technology Assessment, *Flat Panel Displays in Perceptive*, OTA-ITC-631, Washington, DC: U.S. Government Printing Office, September, 1995.

35 Ibid.

Technology	Description	Applicability to DfE Project
	AMLCD Switch Types:	
	(2a) Thin-film transistor (TFT): The transistor acts as a valve allowing current to flow to the pixel when a signal is applied. The transistors are made of various materials including: amorphous silicon (a:Si), polycrystalline silicon (p:Si), non-Si[CdSe].[36] Two different TFT light modulating modes are twisted nematic (TN) and in-plane switching (IPS).[37] In comparison to the TN mode, the IPS mode requires more backlight but fewer manufacturing steps.	The current standard AMLCD switching mechanism for computer displays is a:Si TFT. Polycrystalline Si is not suitable for larger than about 5" displays. Both the TN and IPS a:Si TFT AMLCD technologies are analyzed in the DfE project.
	(2b) Diode matrix: The diode acts as a check valve. When closed, it allows current to flow to the pixel charging it. When opened, the pixel is disconnected and the charge is maintained until the next frame.[38]	The diodes are found to short easily and must be connected in series to achieve long life usability. The diode displays are also limited in size to smaller than that of the functional unit defined for the DfE study.
	(2c) Metal-insulator metal (MIM): The MIM is a diode type switch using metal-insulated-metal fabrication techniques.[39]	Temperature sensitive, which creates gray scale nonuniformities. They are also size-limited, like other diode type displays and therefore not included in the study.
(3) Active-addressed LCD	Hybrid of passive and active matrix. The pixels are addressed using signals sent to the column and row as determined using an algorithm encoded into an integrated circuit (IC). The IC drives each row of pixels more or less continuously and drives multiple rows at one time.[40]	Employed in notebook and desktop monitors >12.1". However, they need special drivers[41] have slow response times, and their contrast worsens as panel size increases. Therefore, this technology does not meet the specifications of the functional unit and is excluded from evaluation in the DfE study.
(4) Plasma-addressed liquid crystal (PALC)	The pixel is addressed using row electrodes, which send the signal, and column gas channels, which conduct a current when ionized.[42]	PALC displays are in development to be used as large low cost displays. Production of the displays have not yet occurred and they are not included in the study.

[36] Castellano, J., *Handbook of Display Technology*, Stanford Resources, Inc., San Jose, CA., 1992.
[37] *DsiplaySearch FPD Equipment and Materials Analysis and Forecast*, Austin, TX, 1998.
[38] Castellano, J., *Handbook of Display Technology*, Stanford Resources, Inc., San Jose, CA., 1992.
[39] Office of Technology Assessment, *Flat Panel Displays in Perceptive*, OTA-ITC-631, Washington, DC: U.S. Government Printing Office, September, 1995.
[40] Ibid.
[41] Ibid.
[42] Ibid.

Technology	Description	Applicability to DfE Project
(5) Ferroelectric LCDs (FLCD or FELCD)	The pixel is addressed using positive or negatives pulses to orient the crystals. The positive pulse allows light to pass (light state) and the negative pulse causes the blockage of light (dark state).[43] A ferroelectric liquid crystal is bistable and holds its polarization when an electric field is applied and removed.[44] They are also called surface stabilized ferroelectric (SSF) LCDs.	Has high resolution with very good brightness, but limited color palette.[45] Limited color palette does not meet color specification of functional unit.
Plasma Display Panels (PDP)	An inert gas (e.g., He, Ne, Ar) trapped between the glass plates emits light when an electric current is passed through the matrix of lines on the glass. Glow discharge occurs when ionized gas undergoes recombination. Ionization of atoms occurs (electrons are removed), then electrons are recombined to release energy in the form of light. Full color plasma displays use phosphors that glow when illuminated by the gas.[46]	Established technology. Good for large screens (e.g., wall-mounted televisions), but are heavier and require more power than LCDs.[47] Designed for large screens and are larger displays than specified for desktop applications. Therefore, not included in the study.
Electroluminescent Displays (EL)	A phosphor film between glass plates emits light when an electric field is created across the film.[48] EL uses a polycrystalline phosphor (similar to LED technology, which is also an electroluminescent emitter, but uses a single crystal semi-conductor). ELs are doped (as a semiconductor) with specific impurities to provide energy states that lie slightly below those of mobile electrons and slightly above those of electrons bound to atoms. Impurity states are used to provide initial and final states in emitting transitions.[49] Also referred to as thin-film EL (TFEL). Variations: AC thin-film EL (AC-TFEL), active matrix EL (AMEL), DC EL, organic EL.	Lightweight and durable. Used in emergency rooms, on factory floors, and in commercial transportation vehicles.[50] Problems found in the power consumption and controlling of gray levels. Targeted toward military, medical, and high-end commercial products; therefore not included in the scope of the DfE project.

[43] Castellano, J., *Handbook of Display Technology*, Stanford Resources, Inc., San Jose, CA., 1992.
[44] Peddie, Jon, *High Resolution Graphics Design Systems*, McGraw Hill, New York, NY, 1994.
[45] Ibid.
[46] Office of Technology Assessment, *Flat Panel Displays in Perceptive*, OTA-ITC-631, Washington, DC: U.S. Government Printing Office, September, 1995.
[47] Ibid.
[48] Ibid.
[49] Peddie, Jon, *High Resolution Graphics Design Systems*, McGraw Hill, New York, NY, 1994.
[50] Office of Technology Assessment, *Flat Panel Displays in Perceptive*, OTA-ITC-631, Washington, DC: U.S. Government Printing Office, September, 1995.

Technology	Description	Applicability to DfE Project
Field Emission Displays (FED)	Flat CRT with hundreds of cathodes (emitters) per pixel (form of cathodeluminescent display); eliminates single scanning electron beam of the CRT. Uses a flat cold (i.e., room temperature) cathode to emit electrons. Electrons are emitted from one side of the display and energize colored phosphors on the other side.[51]	Not commercially available, but anticipated to fill many display needs.[52] Could potentially apply in all LCD and CRT applications. High image quality as with CRT, but less bulky and less power use than with CRT. A number of roadblocks to this technology taking over the AMLCD market include proven manufacturing processes (problems found in the reliability and reproducibility of the devices), efficient low-voltage phosphors, and high voltage drivers. The technology is targeted toward military, medical and high-end commercial products and not included in the DfE study.
Vacuum Fluorescent Displays (VFD)	Form of cathodeluminescent display that employs a flat vacuum tube, a filament wire, a control grid structure, and a phosphor-coated anode. Can operate at low voltages, because very thin layers of highly efficient phosphors are coated directly onto each transparent anode.[53]	VFDs offer high brightness, wide viewing angle, multi-color capability, and mechanical reliability. Used in low information content applications (e.g., VCRs, microwaves, audio equipment, automobile instrument panels). No significant uses seen for computer displays.[54]
Digital Micromirror Devices (DMD)	Miniature array of tiny mirrors built on a semiconductor chip. The DMD is used in a projector that shines light on the mirror array. Depending on the position of a given mirror, that pixel in the display reflects light either onto a lens that projects it onto a screen (resulting in a light pixel) or away from the lens (resulting in a dark pixel).[55]	Just beginning to be used mainly as projection devices, and has not been developed for use that would match the functional unit of the DfE study.[56]

[51] Office of Technology Assessment, *Flat Panel Displays in Perceptive*, OTA-ITC-631, Washington, DC: U.S. Government Printing Office, September, 1995.
[52] Ibid.
[53] Peddie, Jon, *High Resolution Graphics Design Systems*, McGraw Hill, New York, NY, 1994.
[54] Ibid
[55] Office of Technology Assessment, *Flat Panel Displays in Perceptive*, OTA-ITC-631, Washington, DC: U.S. Government Printing Office, September, 1995.
[56] Ibid.

Technology	Description	Applicability to DfE Project
Light Emitting Diodes (LED)	The LED device is essentially a semiconductor diode, emitting light when a forward bias voltage is applied to a p-n junction. The light intensity is proportional to the bias current and the color dependent on the material used. The p-n junction is formed in a III-V group material, such as aluminum, gallium, indium, phosphorous, antimony, or arsenic.	For low information display applications, which makes it not capable of meeting the requirements of the functional unit of the study. Color, power, and cost limitations prevent the emergence into the high information display market.[57]
Electrochromic Display	Open-circuit memory using liquid electrolytes.[58] Non-emitter (as LCDs), as opposed to emitters (e.g., EL, FED, PDP).	Outstanding contrast and normal and wide viewing angles, open-circuit memory. Complex and costly, involving liquid electrolytes, poor resolution, poor cycle life, lack of multicolor capability, etc. Not suitable for computer displays in past; however, new technology may be promising.[59]
Light Emitting Polymers	Developing technology (Holton 1997).[60]	Developing technology.

[57] Castellano, J., *Handbook of Display Technology,* Stanford Resources, Inc., San Jose, CA., 1992.
[58] Peddie, Jon, *High Resolution Graphics Design Systems*, McGraw Hill, New York, NY, 1994.
[59] Ibid.
[60] Holton, W.C., "Light-emitting polymers: increasing promise," *Solid State Technology*, vol. 40, no.. 5, p. 163, May 1997.